The Cornell/BNL FFAG-ERL Test Accelerator: Cβ

eRHIC prototype

Georg Hoffstaetter (Cornell) for the Cβ collaboration

- Project Leader: Dejan Trbojevic
- Project Monitor: Wolfram Fischer
- Cornell Principal Investigator: Georg Hoffstaetter
- Cornell Project Manager: Bruce Dunham

CAD – MAC meeting
21 September 2015

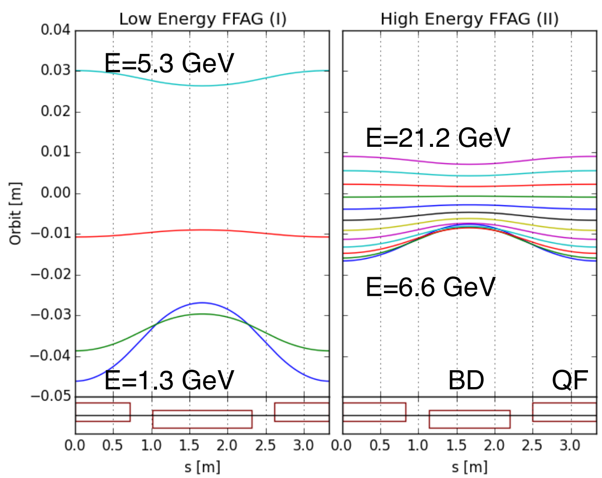
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

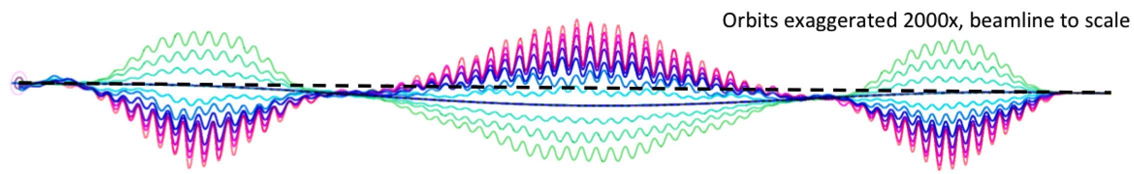
Office of Science
U.S. DEPARTMENT OF ENERGY

eRHIC ERL has 16 turns in only 2 NS-FFAG arcs !

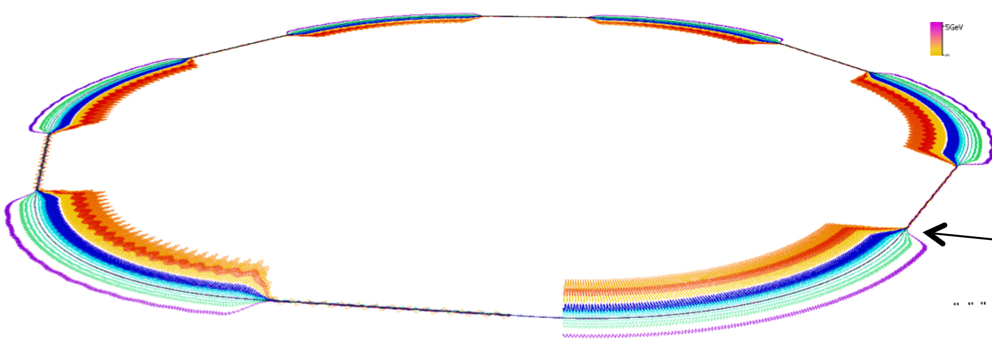
- eRHIC uses two FFAG beamlines to do multiple recirculations. (FFAG-I: 1.3-5.4 GeV, FFAG-II: 6.6-21.2 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can be used for the FFAG beamline magnets (no need for power supplies/cables and cooling).



@S.Brooks, D.Trbojevic

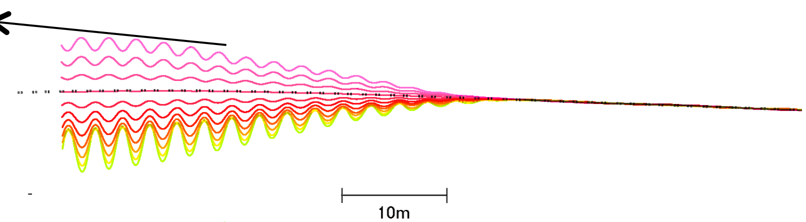


Orbits in Detector bypass section



Quad offsets evolve adiabatically

Orbits in Transition section



Each of two eRHIC FFAGs contain 1066 FFAG cells

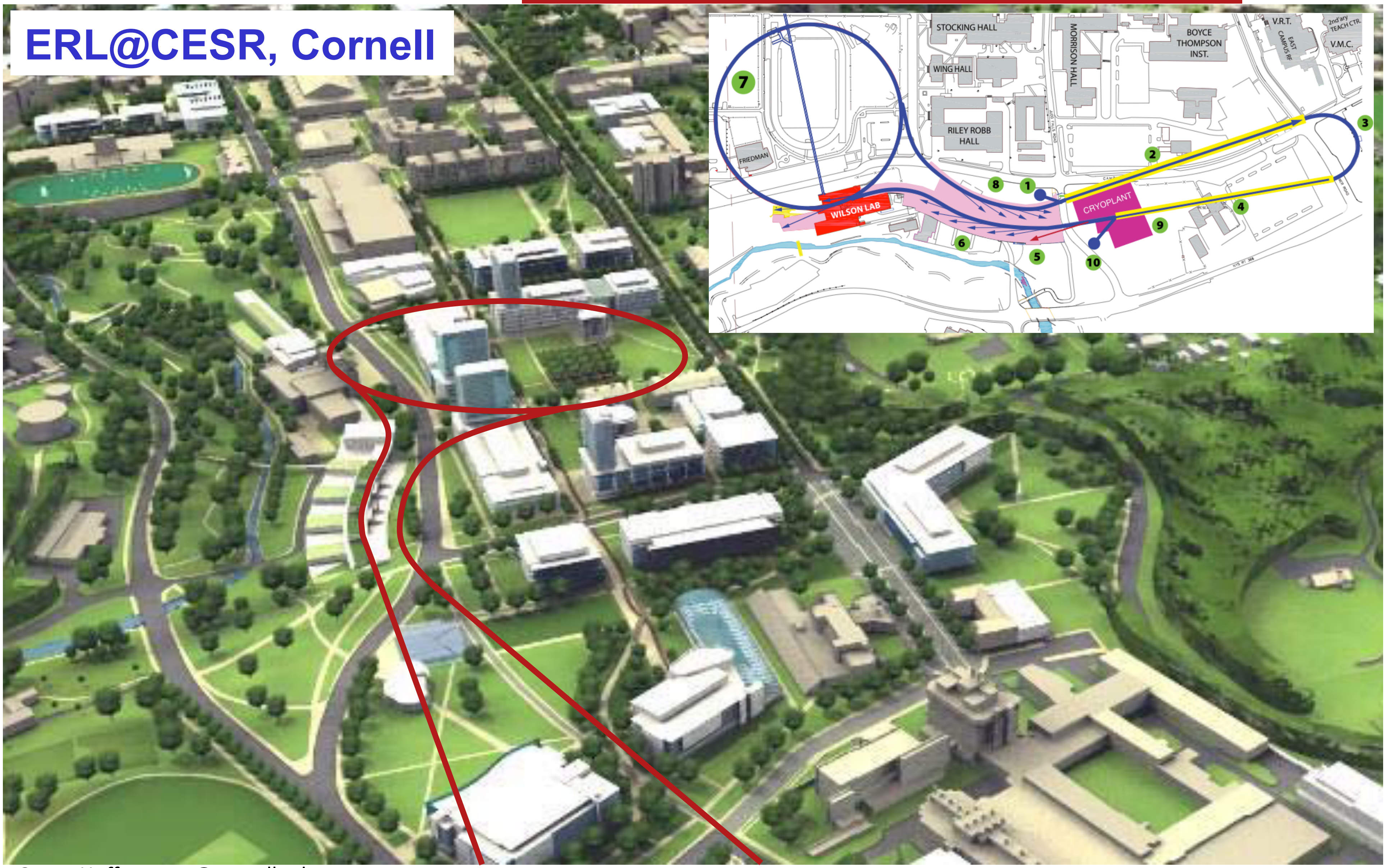
Risks for eRHIC

Some of the most important risk items for eRHIC:

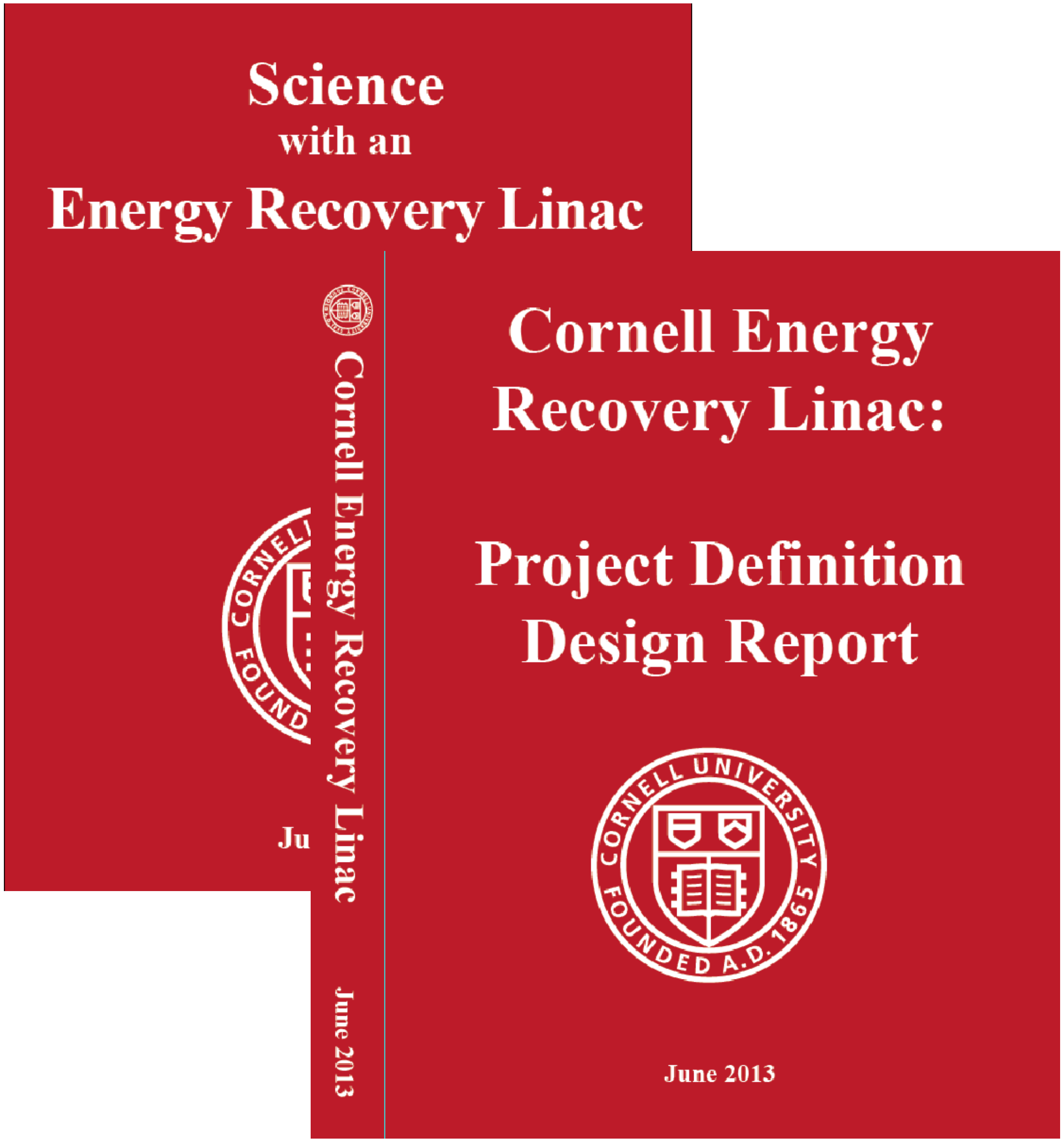
1) FFAG loops with a factor of 4 in momentum aperture.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) Matching and correction of multiple simultaneous orbits.
   d) Matching and correction of multiple simultaneous optics.
   e) Path length control for all orbits.

2) Multi-turn ERL operation with a large number of turns.
   a) HOM damping.
   b) BBU limits.
   c) LLRF control and microphonics.
   d) ERL startup from low-power beam.

ERL as extension of CESR



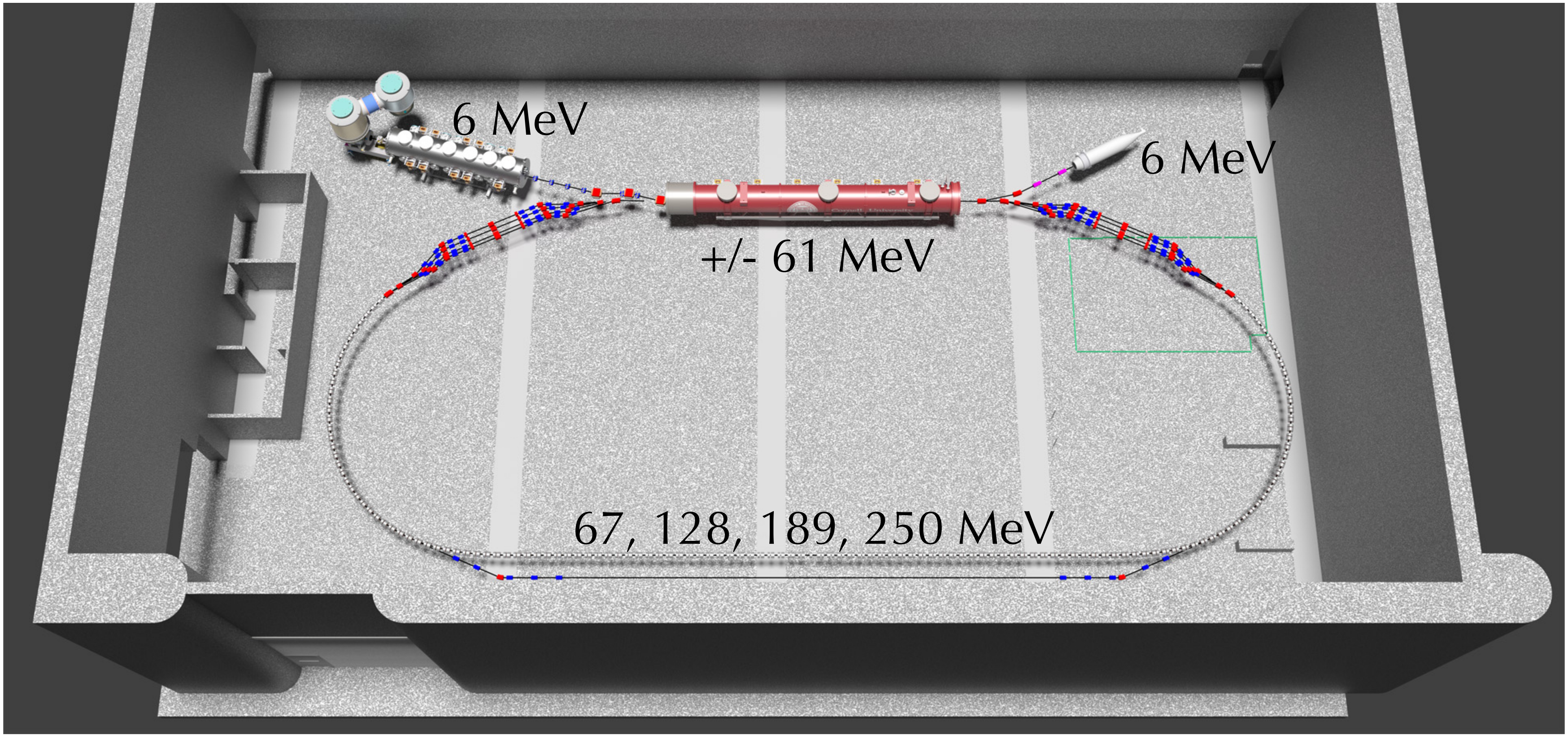
ERL documentation: (1) Science, (2) Generic design



- Science case gathered in international workshops
- Design report
  - 530 pages between conceptual design and engineering design
  - Access at www.classe.cornell.edu/ERL/PDDR
- Also
  - Electron beam construction (from RI)
  - Cryoplant (from Linde and Air Liquide)

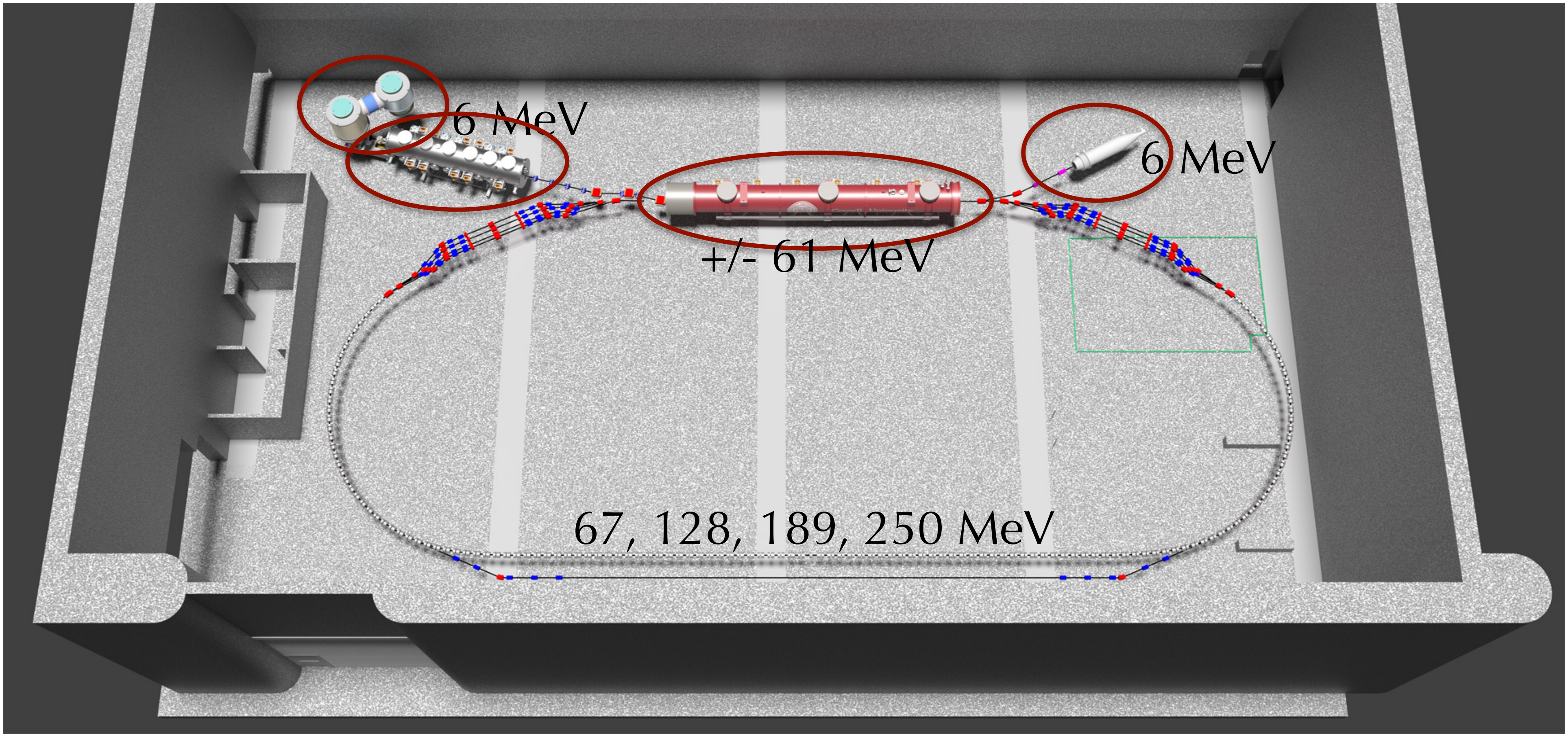
Prototype eRHIC ERL @ Cornell

- NS-FFAG arcs, four passes (like first eRHIC loop)
- Momentum aperture of x4, as for eRHIC (EMMA achieved x1.7, planned x2)
- Uses Cornell DC gun, injector (ICM), dump, SRF CW Linac (MLC)
- Prototyping of essential components of eRHIC design



Existing components @ Cornell

- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)



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The Cornell-BNL FFAG-ERL Test Accelerator

White Paper

A white paper has been written to outline the Cβ concept: arXiv:1504.00588

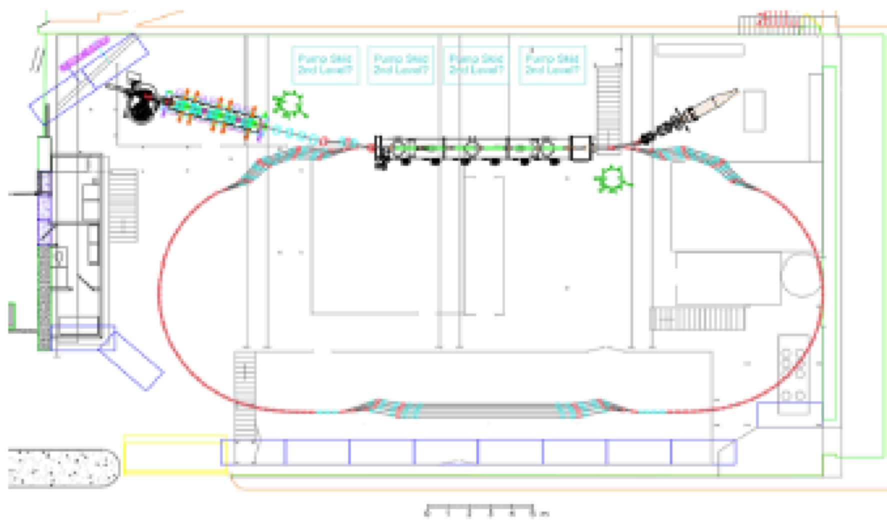
Ivan Bazarov, John Dobbins, Bruce Dunham, Georg Hoffstaetter, Christopher Mayes, Ritchie Patterson, David Sagan

Cornell University, Ithaca NY

Ilan Ben-Zvi, Scott Berg, Michael Blaskiewicz, Stephen Brooks, Kevin Brown, Wolfram Fischer, Yue Hao, Wuzheng Meng, François Méot, Michiko Minty, Stephen Peggs, Vadim Ptitsin, Thomas Roser, Peter Thieberger, Dejan Trbojevic, Nick Tsoupas.

Brookhaven National Laboratory, Upton NY

A Conceptual Design Report (CDR) is in preparation.



December 16, 2014

The Cβ collaboration has:

- Started collaborative discussions in July 2014.
- Weekly phone meetings.
- Three face to face collaboration meetings of about 20 participants. Next one mid June at Stony Brook University.

Beam parameters at the FFAG-ERL

Electrons

Current I of up to 320mA in the linac (eRHIC has 700mA in the Linac)

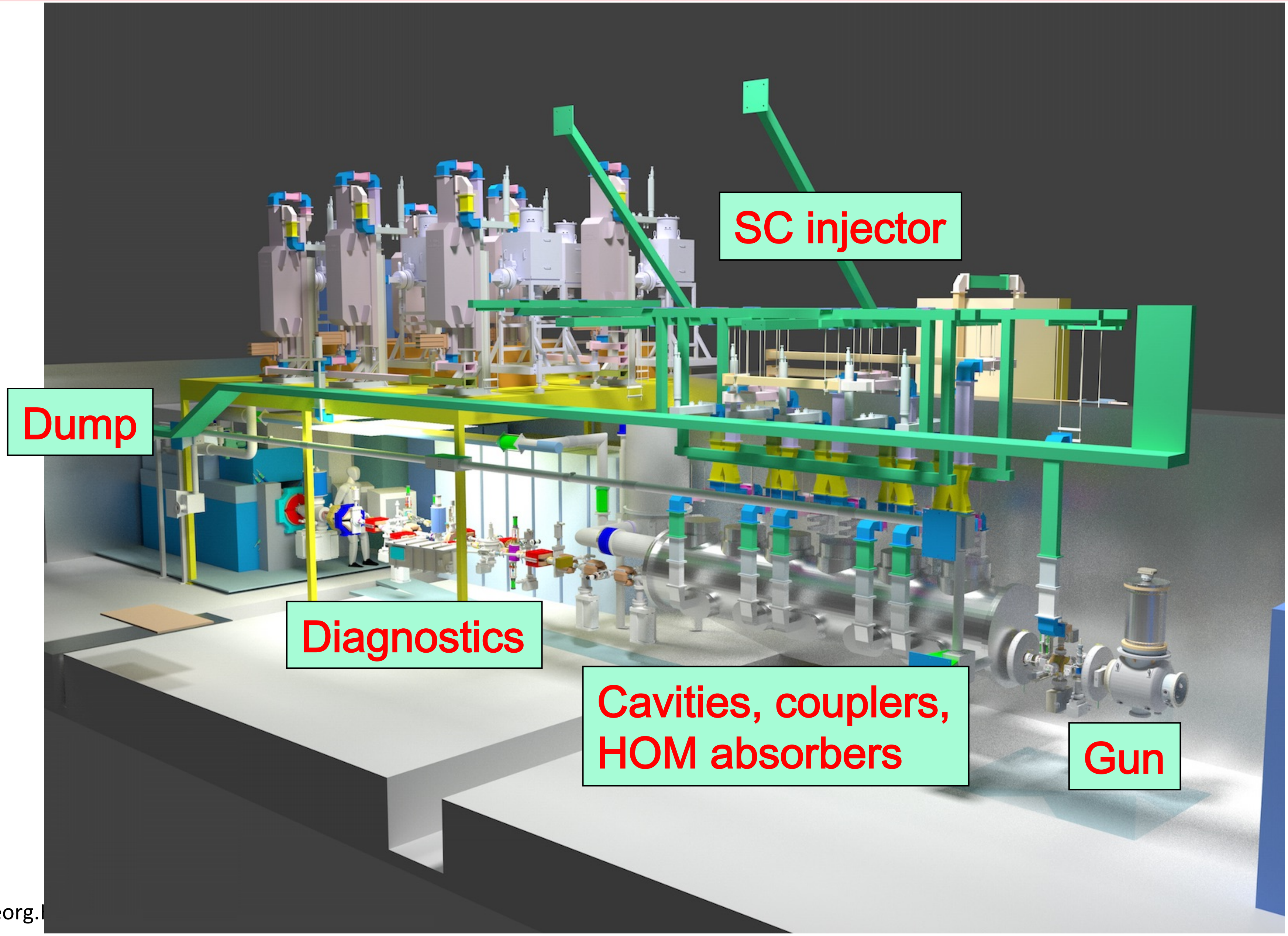
Bunch charge Q of up to 2nC [funded by DOE-NP] (eRHIC 5.3nC)
[to be copied for BNL]

Bunch repetition rate of 1.3GHz/N (e.g. 422.5MHz/13 for eRHIC cavity)

Energy E up to 250 MeV, operating only one cavity in the MLC

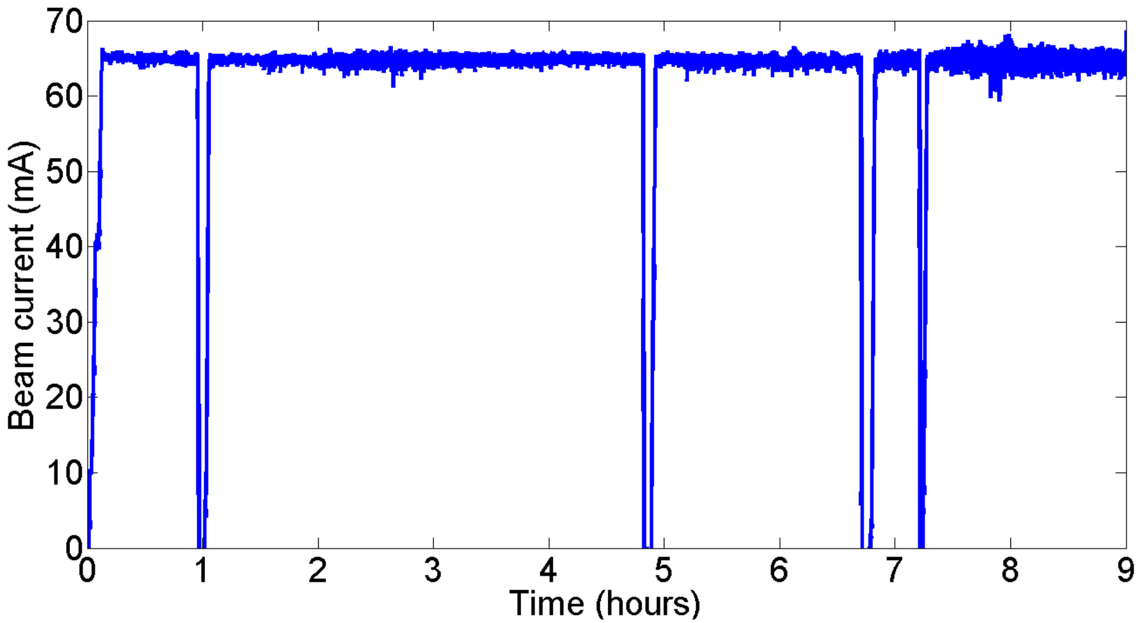
Beams of 100mA for 1 turn and 40mA for 4 turns

Cornell ERL injector prototype



ERL Readiness: high current beam

CLASSE



- Peak current of 75mA (world record)

- NaKSb photocathode
- High rep-rate laser
- DC-Voltage source

Source achievements:

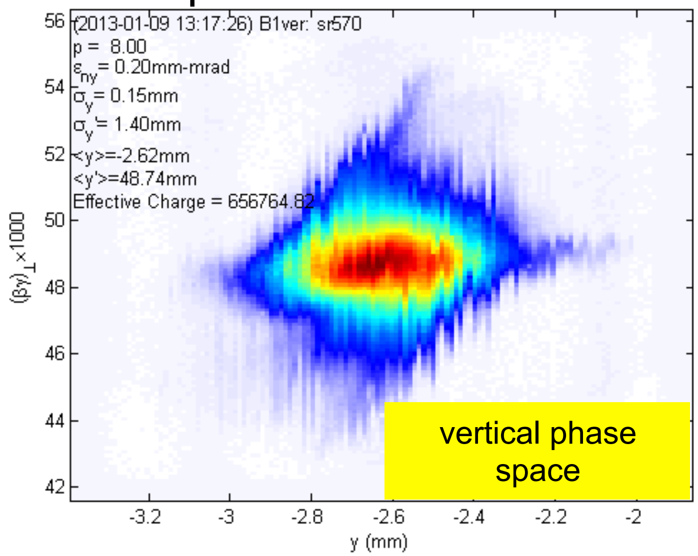
- 2.6 day 1/e lifetime at 65mA
- 8h at 65mA
- With only 5W laser power (20W are available)
- now pushing to 100mA

Simulations accurately reproduce photocathode performance with no free parameters, and suggest strategies for further improvement.

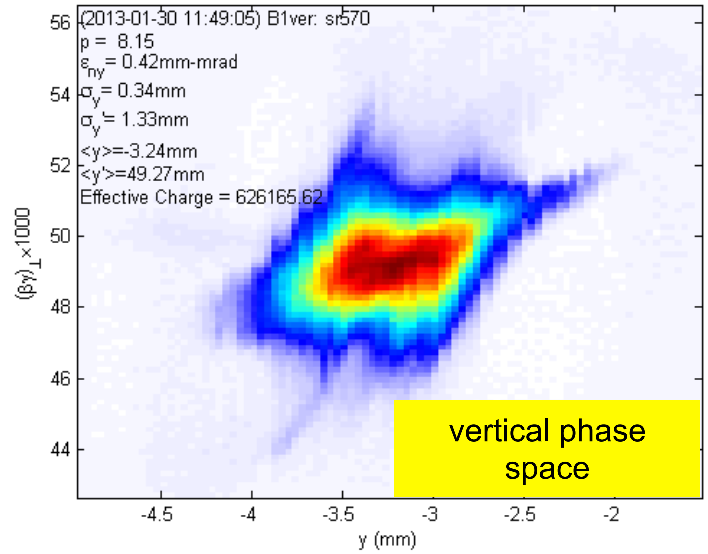
✓ Source current can meet ERL needs

ERL readiness: Beam brightness

20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps

0.23/0.14 mm-mrad | 0.51/0.29 mm-mrad

Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)

0.14/0.09 mm-mrad @ 68% | 0.24/0.18 mm-mrad @ 61%

Phys. Rev. ST-AB 15 (2012) 050703
ArXiv: 1304.2708

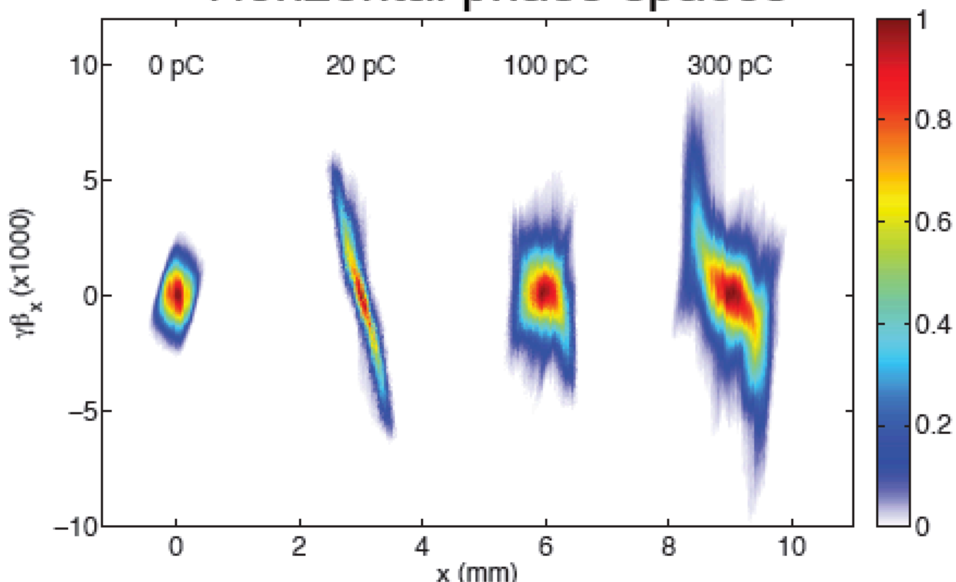
✓ At 5 GeV this gives 20x the world's highest brightness (Petra-III)

Beam tests for LCLS-II

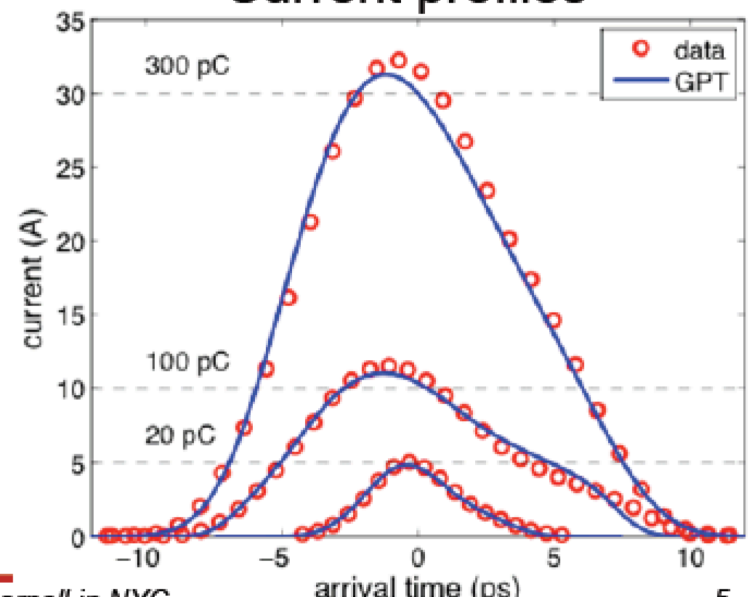
Target specs:

Bunch charge (pC)	Peak current target (A)	Peak current measured (A)	Emittance Target (95%, μm)	Emittance measured (95%, μm)
20	5	5	0.25	H: 0.18, V: 0.19
100	10	11.5	0.40	H: 0.32, V: 0.30
300	30	32	0.60	H: 0.62, V: 0.60

Horizontal phase spaces



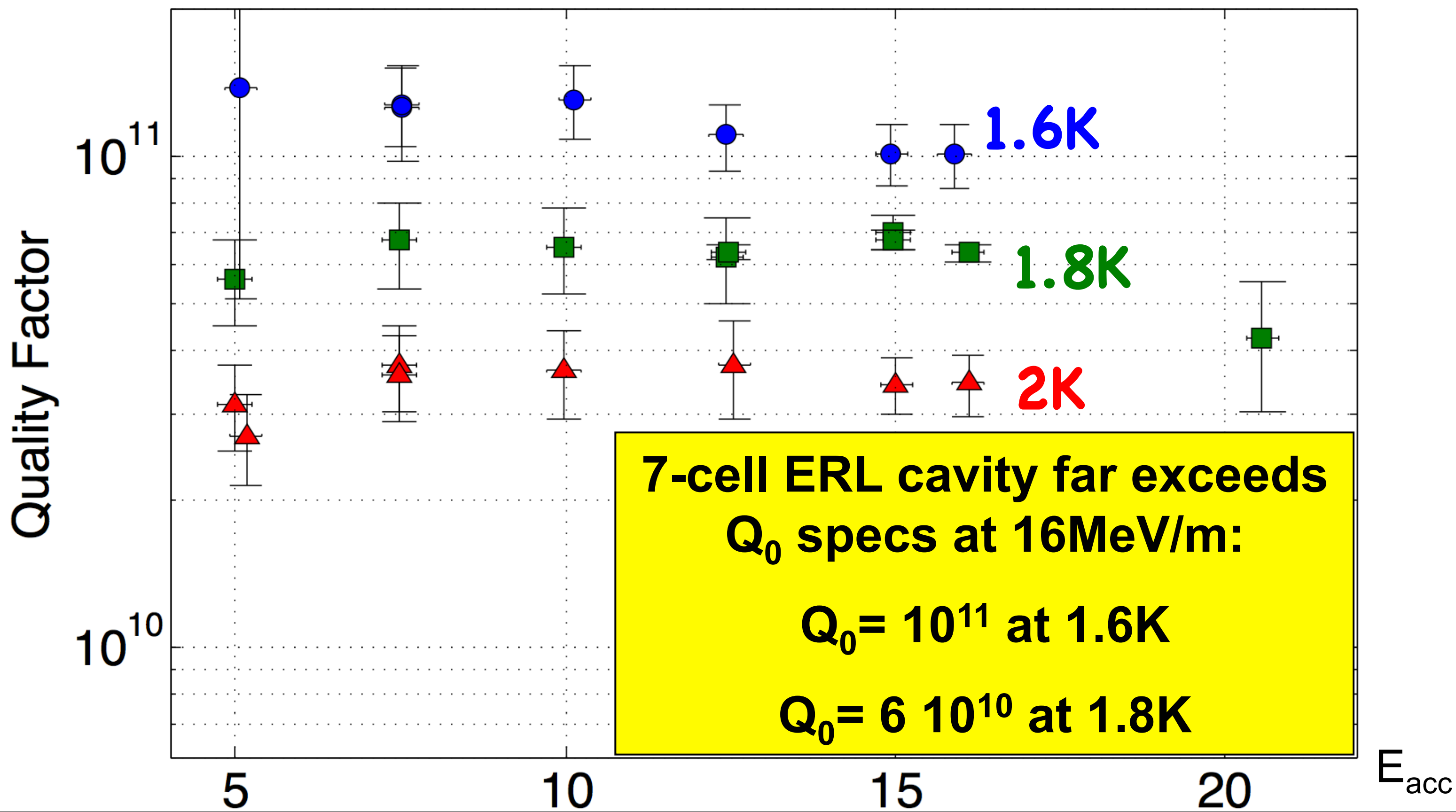
Current profiles



Dec. 12, 2014 *Patterson* *BNL-JLAB-Cornell in NYC* *5*

Low-loss SRF cavities for CW linacs: High Q0

Cavity surface was prepared for high Q_0 while keeping it as simple as possible: bulk BCP, 650C outgassing, final BCP, very uniform 120C bake, HF rinse.



7-cell ERL cavity far exceeds Q_0 specs at 16MeV/m:

Q_0= 10^{11} at 1.6K

Q_0= 6 10^{10} at 1.8K

The achievement of high Q is relevant not only to Cornell's ERL but also to Project-X at Fermilab, to the Next Generation Light Source, to Electron-Ion colliders, spallation-neutron sources, and accelerator-driven nuclear reactors.

MLC construction at Cornell

Main Linac Cryomodule

Assembly completed November 20, 2014. Ready for testing.

Studies already well under way

What BNL gets out of the collaboration: Risk reduction and prototyping.

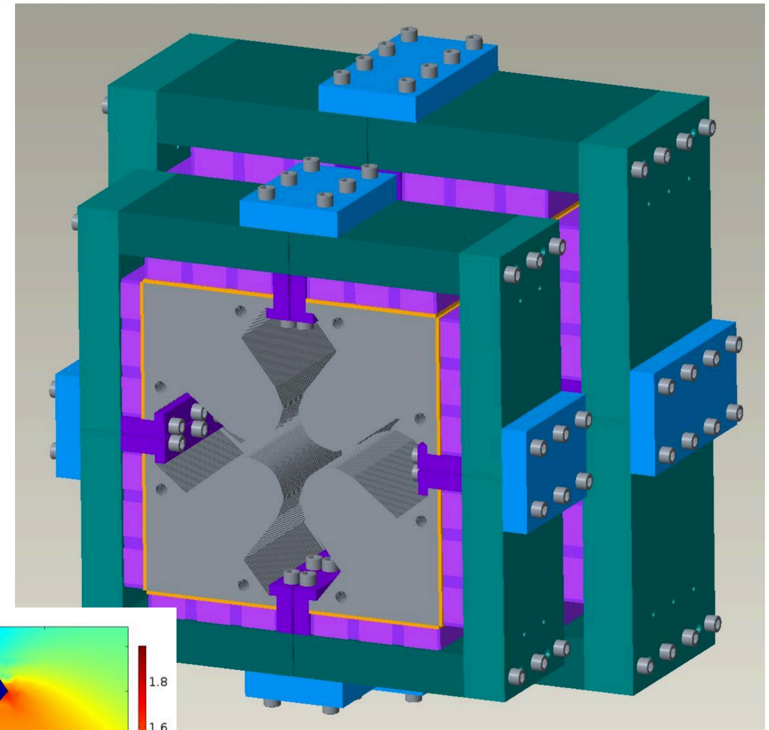
- R&D and prototyping of eRHIC systems, e.g. multi-beam feedback, timing and synchronization, high-current halo control, collimation, LLRF control, ions, CSR, etc.
- Proof of FFAG capabilities, e.g. momentum acceptance of x4, orbit and optics correction with real tolerances, reproducibility of magnet and girder construction, adiabatic FFAG transitions, resonant beam separation, etc.
- Proof of multi-turn ERL operation, BBU studies for 4 turns, operational stability, multi-beam diagnostics possibly for pilot bunches, merger matching.
- After replacing the MLC by an eRHIC cavity: Proof of eRHIC-cavity capabilities, e.g. current limits, RF stability, microphonics control, HOM heating, etc.

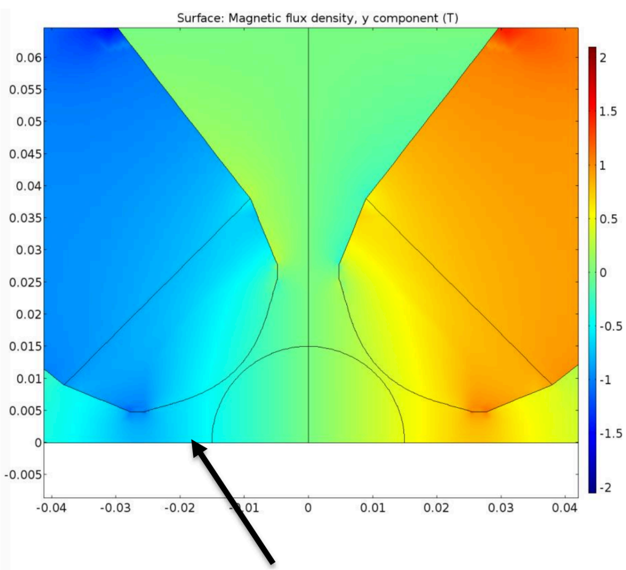
Cornell gets out of the collaboration:

- Forefront research in ERL physics.
- Excellent opportunities to educate accelerator physics students (e.g. for eRHIC).
- A high-brightness beam of moderate energy for physics experiment.

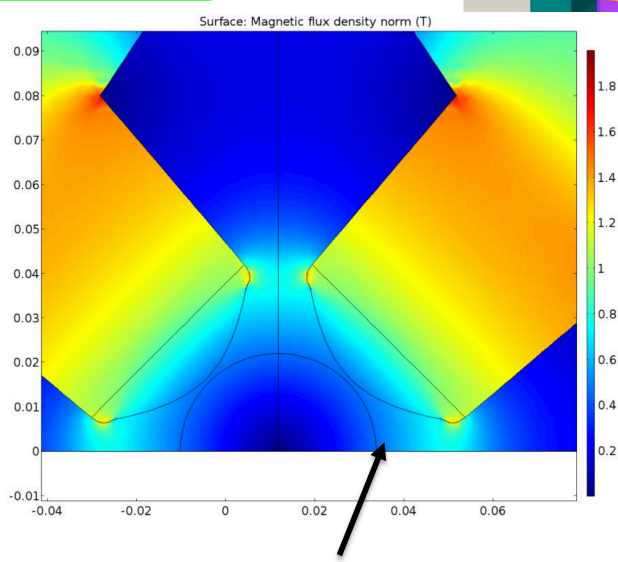
FFAG magnet design for Cβ

- Temperature stabilized using NiFe cross hatches or bars: a few 10^{-4} between 20 and 30^{0}C.
- Comfortable field strengths
- Well controlled cross talk
- Budgetary estimates obtained from 1-year delivery from Radiabeam.





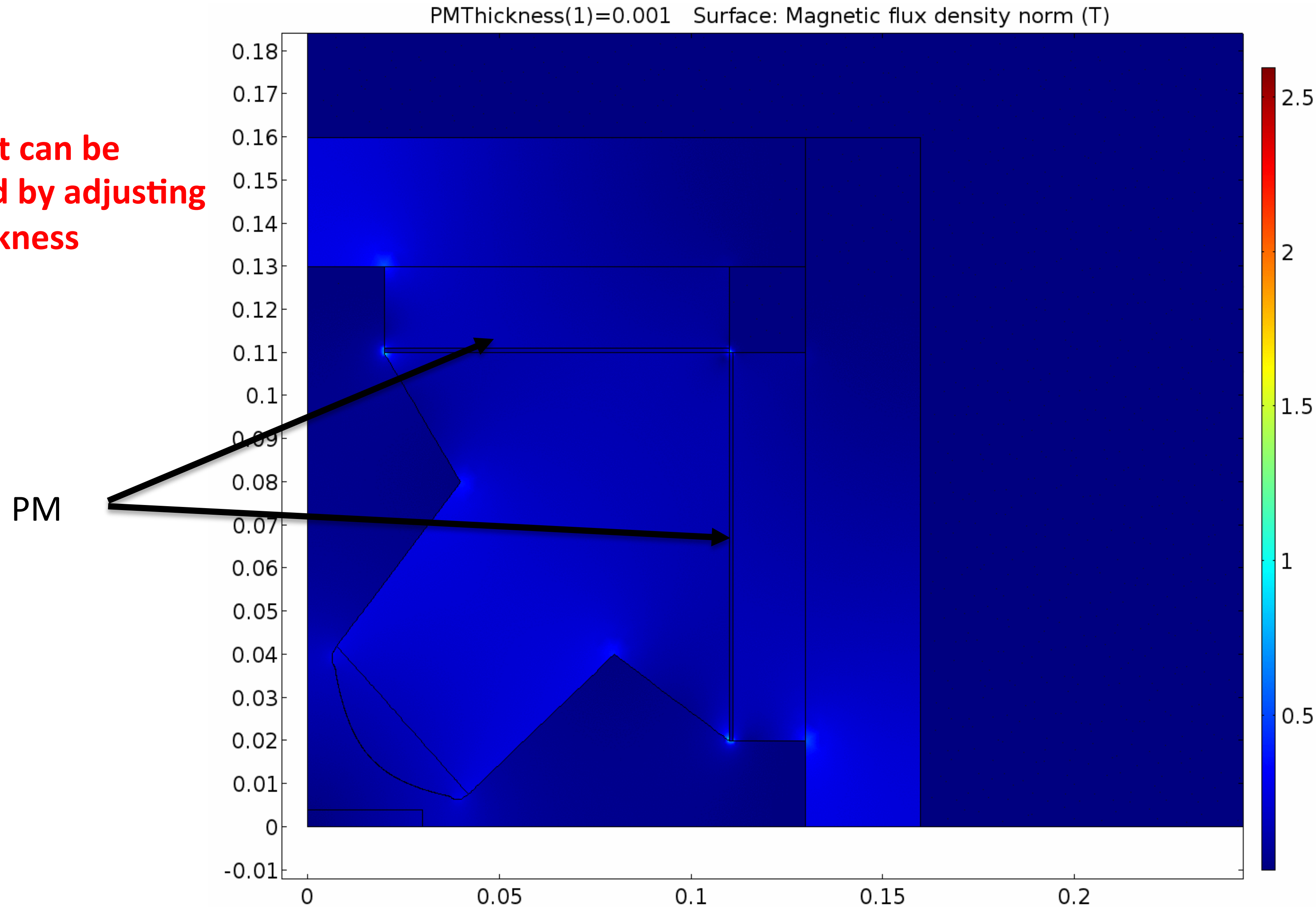
Qf: -0.6T @ -19mm



Qd: -0.4T @ (36-15.9)mm

Changing FFAG magnet strength

Gradient can be Changed by adjusting PM thickness



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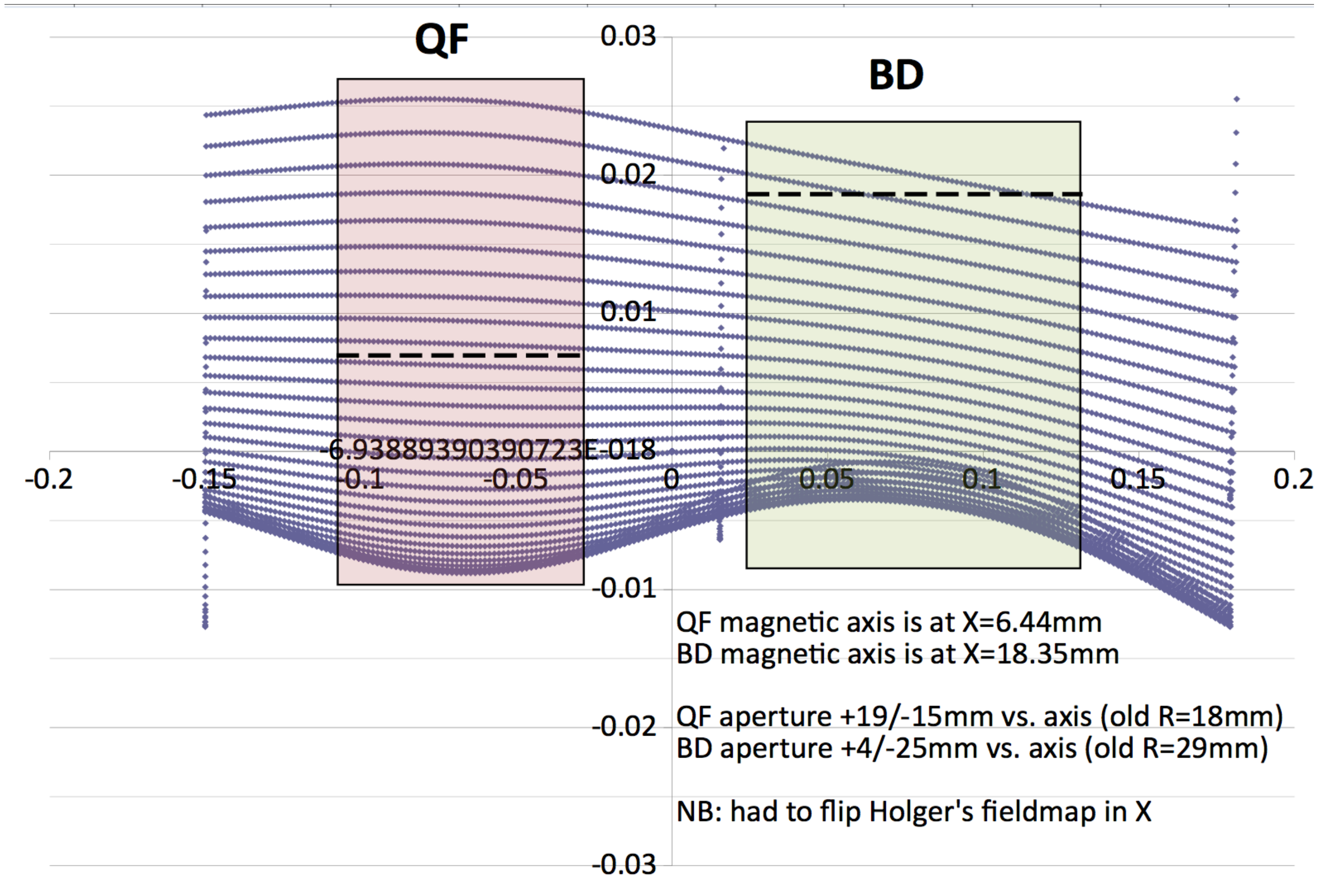
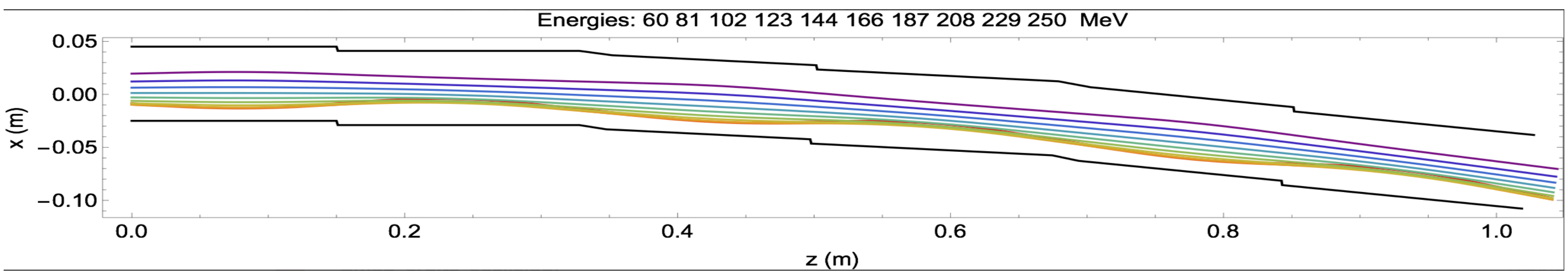
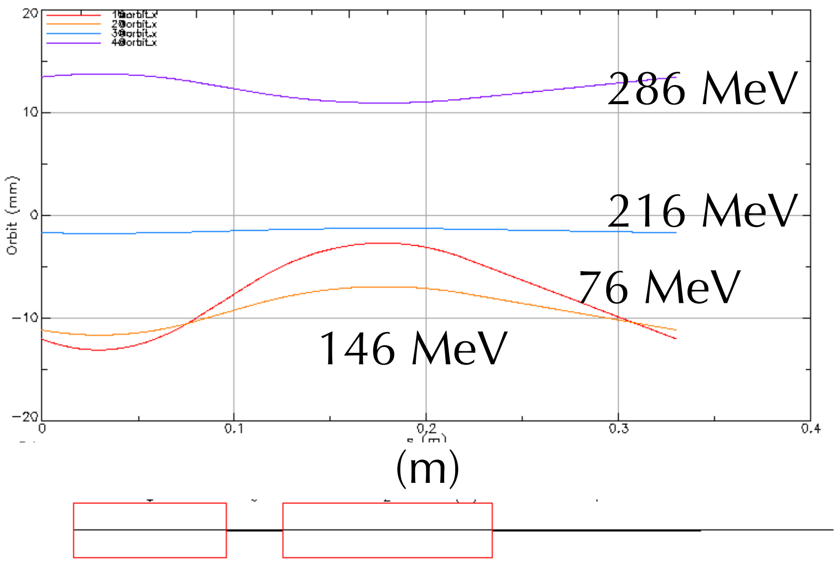
Orbits for 3D simulated field maps





Example study: Orbits for different energies

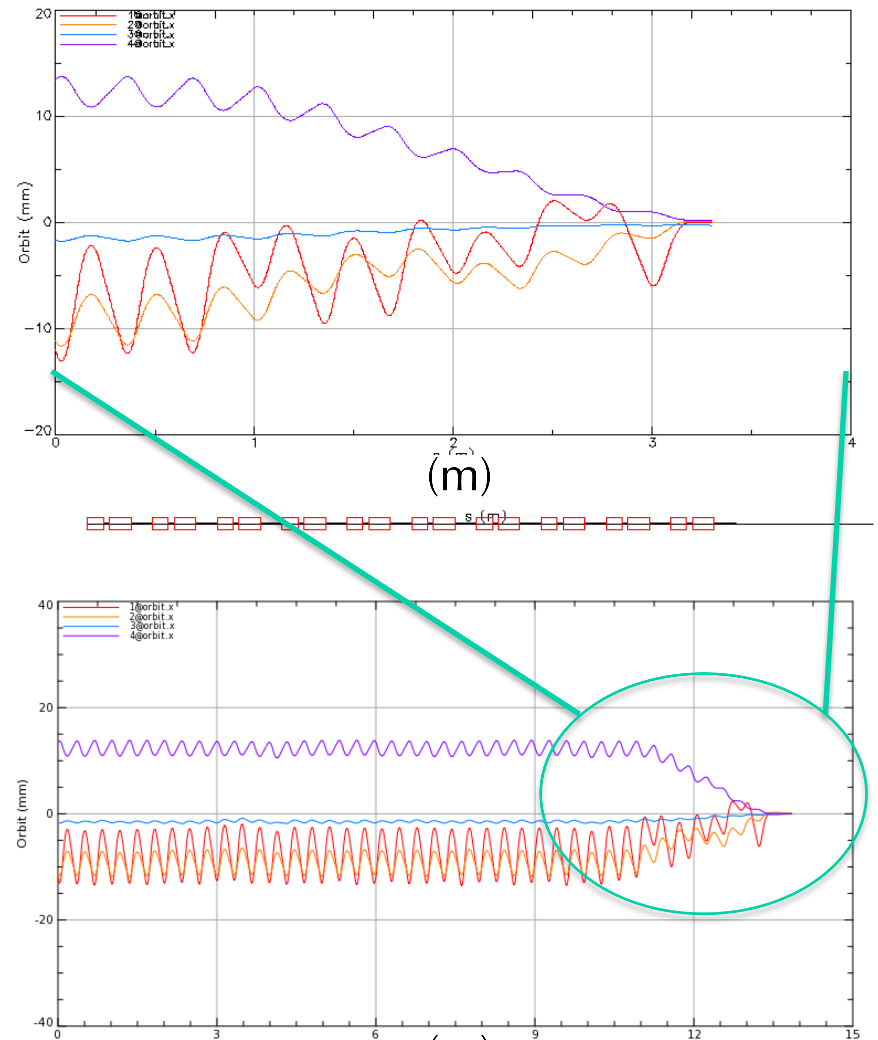
Cell



-3.6 deg

Focus	Defocus
8 cm	11 cm
42.5 T/m	-27.5 T/m
-0.104 T	-0.5044 T

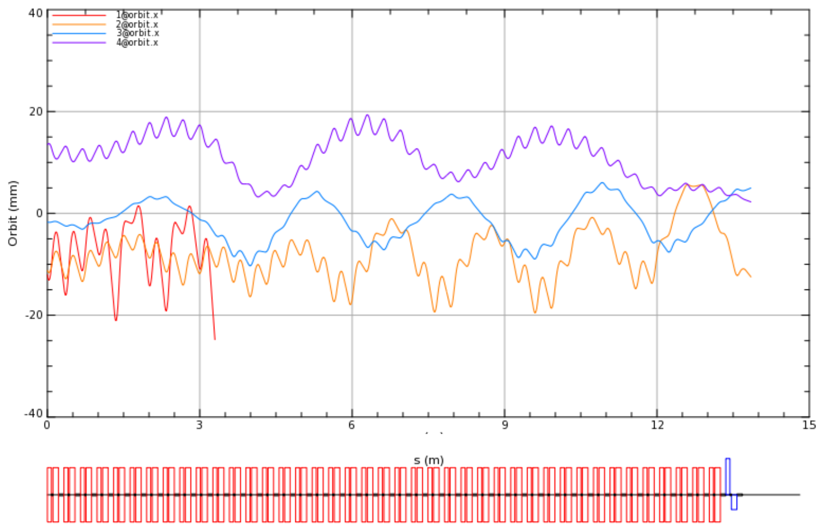
Arc-to-Straight (10 cells)



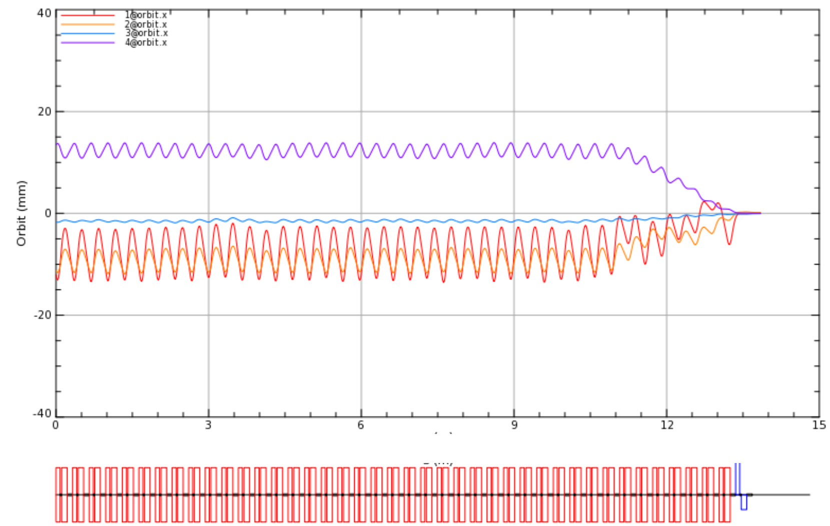
Example study: FFAG ERL orbit corrections

500 um rms x offset errors

SVD correction given BPM readings for separate beams and correction coils on every other dipole



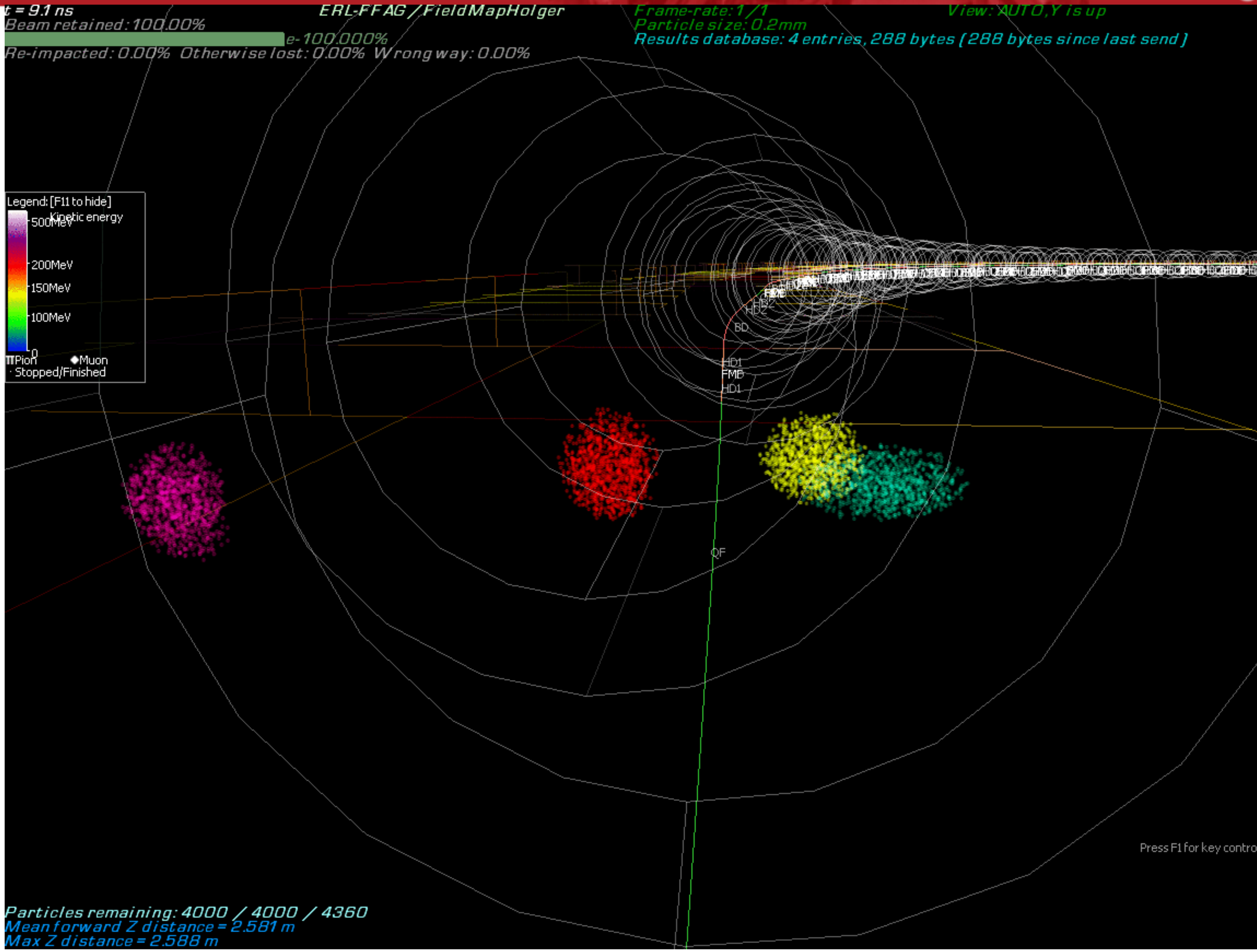
Full FFAG arc



Full FFAG arc

(m)

Bunche dynamics in 3D field maps

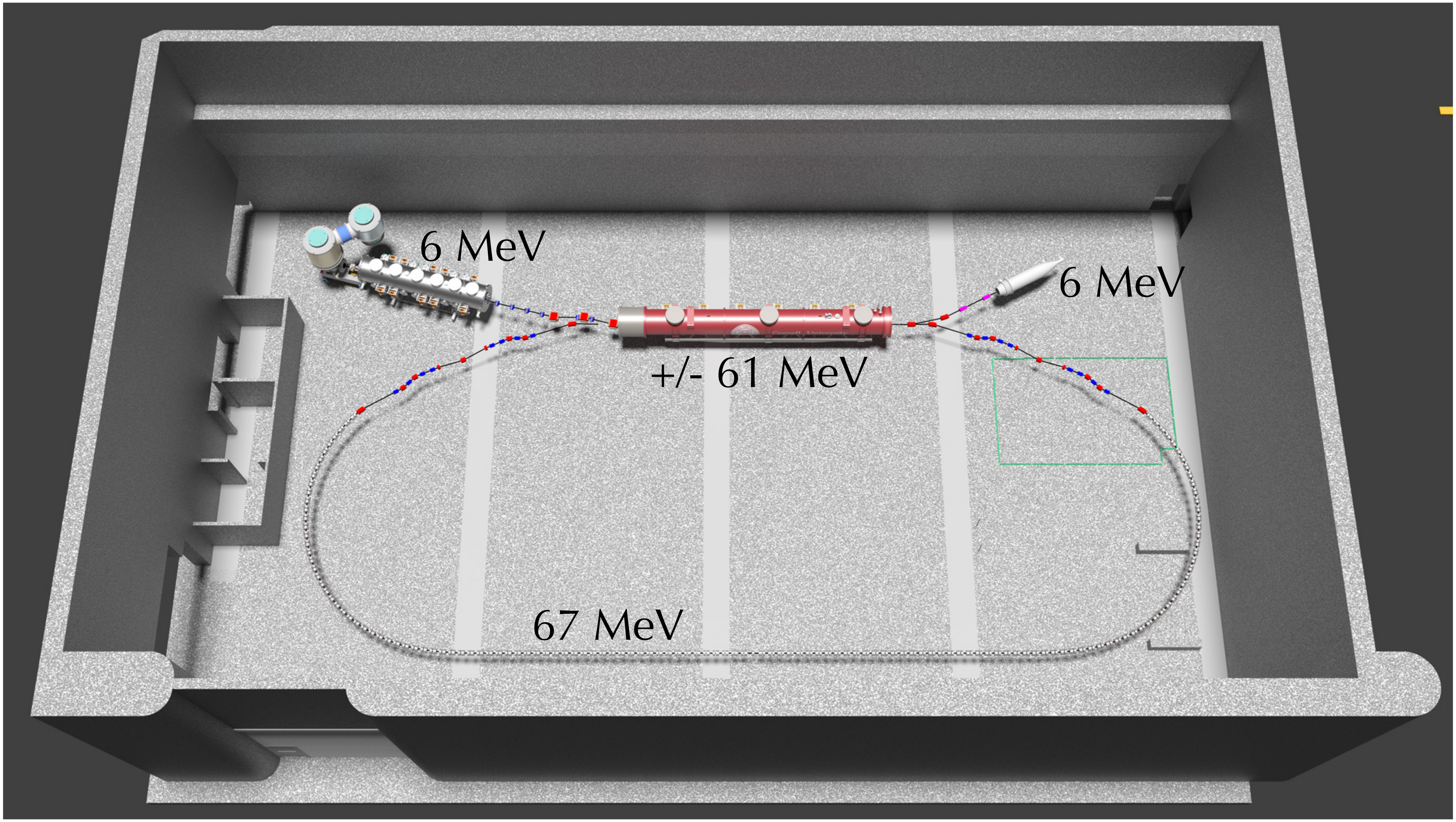


L0E cleanout for Cβ ERL

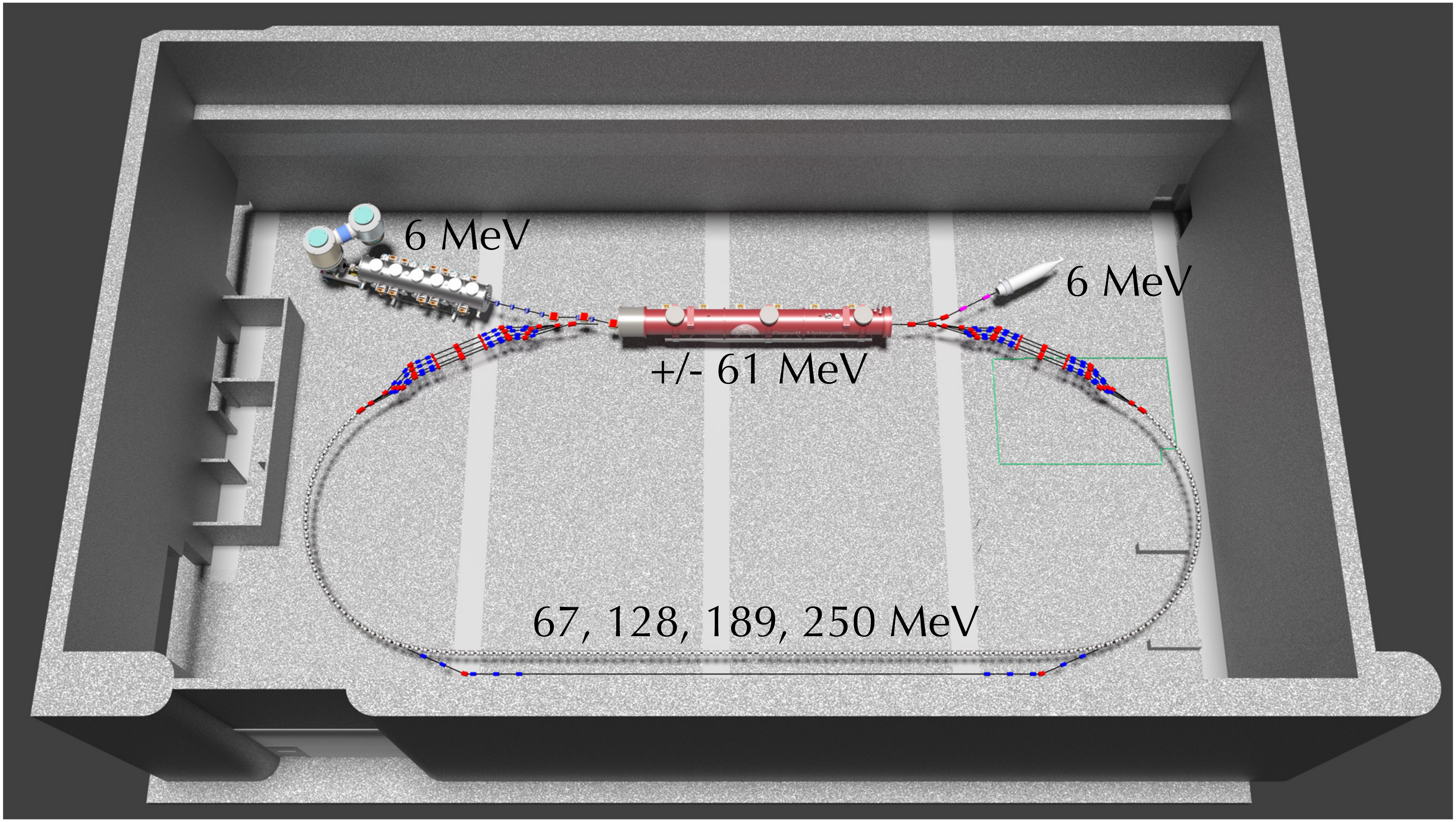
L0E cleaned out for Cβ ERL

L0E cleaned with Cβ ERL

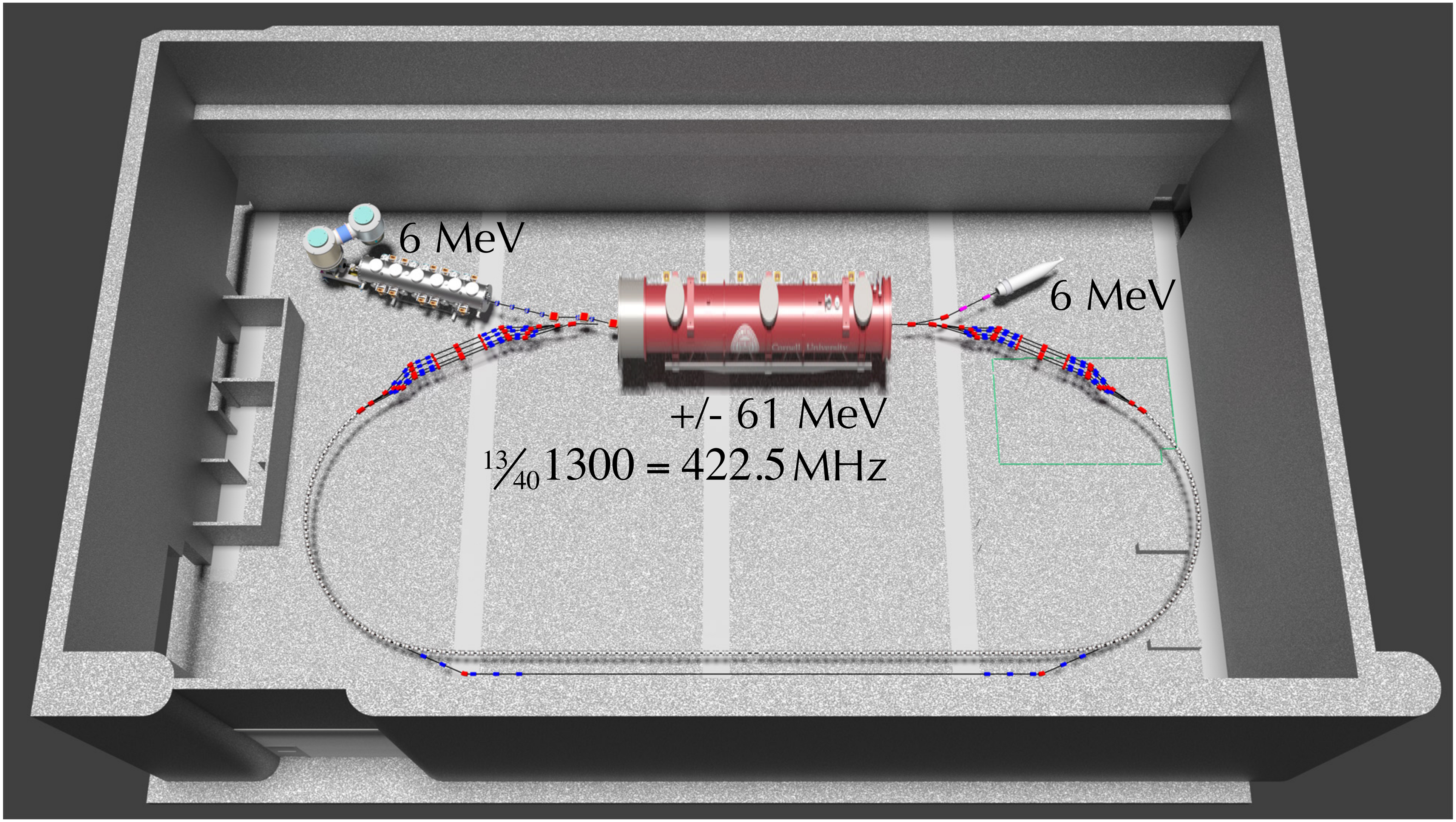
1st stage: 1-turn ERL for 67 MeV



2nd stage: 4-turn FFAG ERL



3rd stage: 4-turn FFAG ERL with eRHIC cavity



Unique capabilities of Cβ, essentail for eRHIC risk reduction

- Cβ will be the first accelerator in the world to include any of the following things, which are all required by the eRHIC design
  - ERL using FFAG recirculating arcs
  - Linear field FFAG with momentum range of 4x
  - Adiabatic transition from curved to straight FFAG
  - Permanent magnets (PMs) used in an FFAG
  - NdFeB PMs used for main beam steering
  - PMs used in ERL return arcs
  - Multi-pass superconducting ERL

Phase 1&2

← Phase 3&4

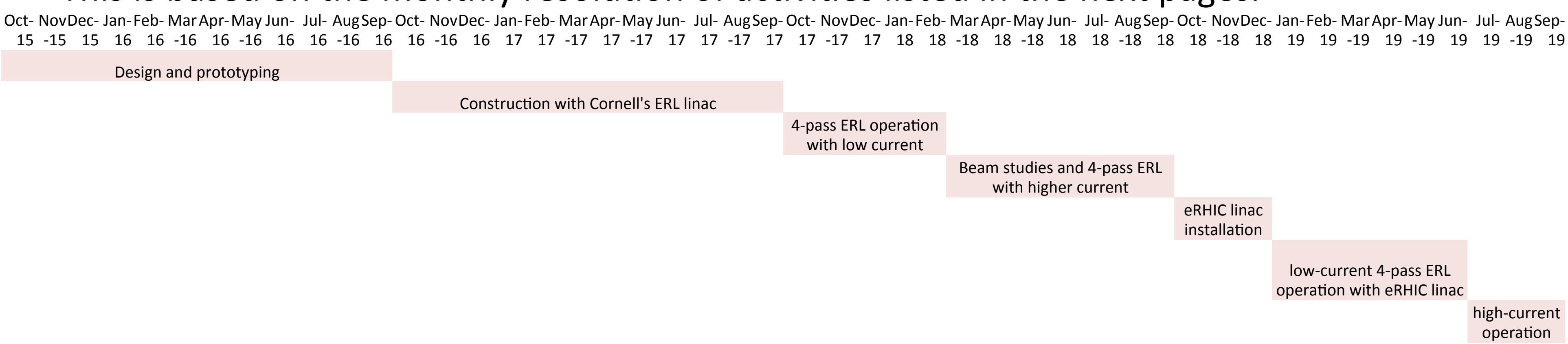
Milestones

- Deliverables:
  - Completed eRHIC prototype accelerator (Cornell University site location)
  - Commission the ERL NS-FFAG eRHIC prototype.
  - **Perform eRHIC related experiments: accelerate 4 times in energy with the energy recovery for four energies, perform the orbit, gradient, time of flight correction, etc.**
- Key Performance Parameters (KPP)
  - Demonstrate orbit corrections for all energies
  - Demonstrate a factor of 4 momentum acceptance in the FFAG
  - Demonstrate 4-pass recirculation with energy recovery at an average current of 1 mA
  - Demonstrate extraction for the highest energy pass
- Ultimate Performance Parameters (UPP)
  - Demonstrate 4-pass recirculation with energy recovery at an average current of 40 mA, with extraction of the highest energy

Milestones (with immediate start)

10/01/2016	Design and prototyping complete
10/01/2017	Construction complete with Cornell's ERL linac
03/01/2018	4-pass ERL operation with low current
10/01/2018	4-pass ERL operation with high current
01/01/2019	eRHIC linac installation
07/01/2019	4-pass ERL operation with eRHIC linac
10/01/2019	4-pass ERL operation with high current

This is based on the monthly resolution of activities listed in the next pages.



Main Work Items (year 1)

Oct 2015 Complete magnet designs for 2 competing options
Optics design
Order RF solid state amplifiers
Order cryogenic pump skids

Nov 2015 Optics design
Build prototypes for 2 magnet types
design trim coils for quad and correction

Dec 2015 Optics design
Test prototype magnets
Choose magnet type
complete trim coil design

Jan 2016 Optics design
Obtain vendor quotes for magnets
Finalize radiation shielding design
Move injector klystrons into position

Feb 2016 Optics design complete
Order permanent magnets
Start clearing out remainder of exp. Hall
Order trim coils

Mar 2016 prototype complete FFAG arc cell structure
Order conventional magnets & PS
Move linac, Icm and gun into final position
Move cryogenic valve box, cryo lines

Apr 2016 Complete MLC RF system installation
vacuum and support structure design
specify and design diagnostic systems
Complete cryo line installation

May 2016 prepare for linac full power tests
vacuum and support structure design
design diagnostic systems
Radiation Permit preparation

Jun 2016 Linac full power tests
design diagnostic systems
continue vacuum design
Radiation permit preparation

Jul 2016 Move CESR RF system, water system
Complete vacuum chamber design
Complete support girder design
Begin shielding block shipping

Aug 2016 prepare for magnet QA
Move CESR RF system, water system
build/order vacuum components
build/order support girders

Sep 2016 prepare for magnet QA
Move CESR RF System, water system
Complete area preparation
Shielding block installation

Main Work Items (year 2)

Oct 2016	PM magnet acceptance and QA Conventional magnet acceptance and QA support girder acceptance shielding block installation
Nov 2016	PM magnet QA Conventional magnet QA assemble/test FFAG girder shielding block installation
Dec 2016	vacuum chamber acceptance/testing order bpm electronics safety system installation radiation permit approval
Jan 2017	vacuum chamber acceptance/testing safety system installation
Feb 2017	construct magnet girder assemblies preliminary safety system checkout
Mar 2017	construct magnet girder assemblies Control system installation safety system installation
Apr 2017	construct magnet girder assemblies Control system installation safety system installation
May 2017	construct magnet girder assemblies install magnet girders install magnet power supplies Control system installation
Jun 2017	install magnet girders install magnet power & water & controls subsystem tests: vacuum, magnets, diagnostics Control system installation
Jul 2017	install magnet girders install magnet power & water & controls subsystem tests: vacuum, magnets, diagnostics Control system installation
Aug 2017	install magnet girders install magnet power & water & controls subsystem tests: vacuum, magnets, diagnostics safety system testing
Sep 2017	subsystem tests: vacuum, magnets, diagnostics safety system certification

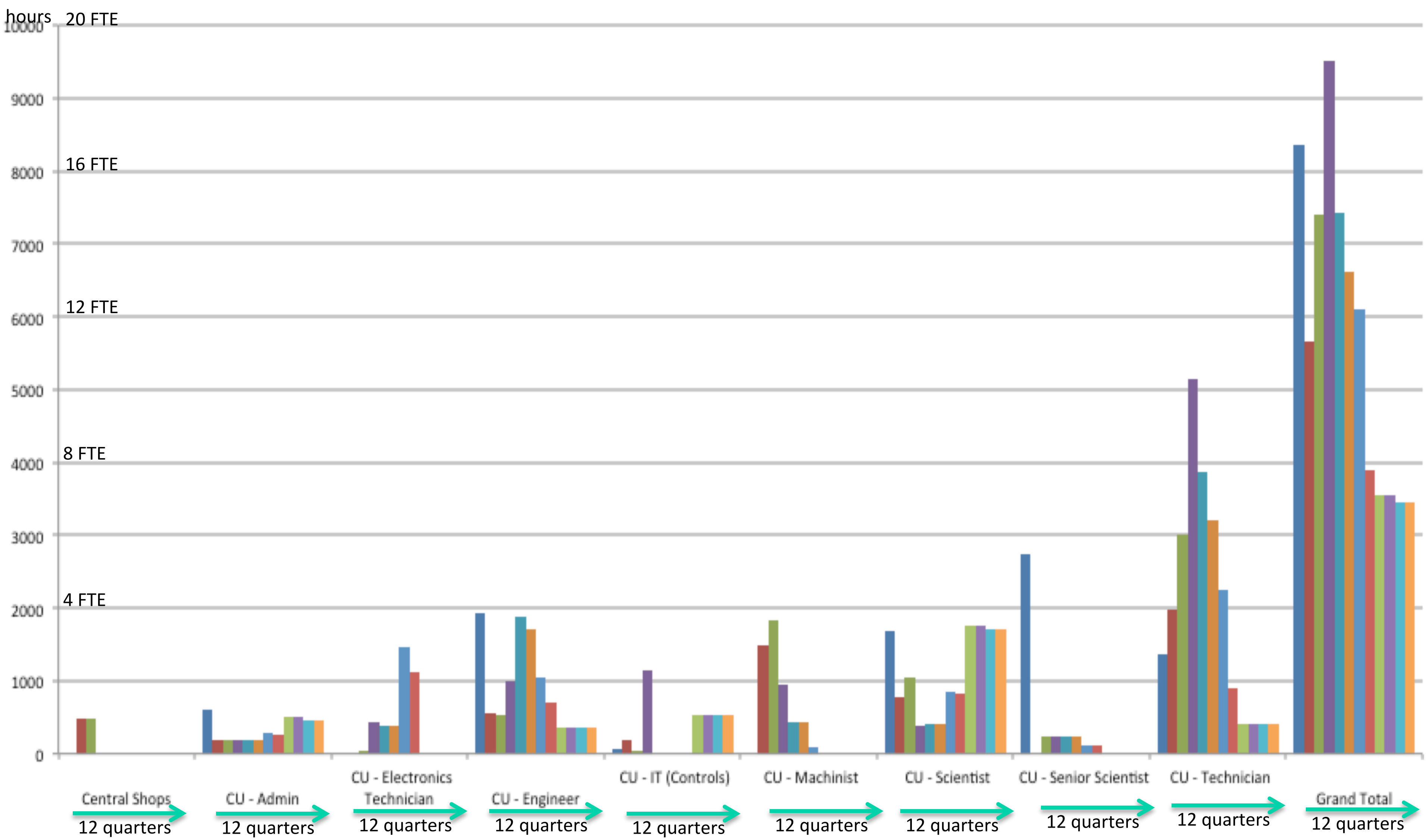
Main Work Items (year 3)

Oct 2017	Initial beam commissioning in pulsed mode Beam through first pass, linac phasing path length adjustment dump optics setup
Nov 2017	demonstrate energy recovery for 1 pass optics in spreaders/recombiners second pass, path length adjust
Dec 2017	third pass, spreaders/recombiners beam quality measurements correction schemes
Jan 2018	fourth pass, spreaders recombiners path length adjustments beam quality measurements
Feb 2018	beam optics verifications, pulsed beam energy acceptance measurements
Mar 2018	high current setup, 1 mA 1 pass and energy recovery
Apr 2018	2, 3 and 4 pass setup high current operations BBU measurements
May 2018	higher current tests, > 1 mA
Jun 2018	chromaticity and emittance growth measurements higher current tests, > 1 mA
Jul 2018	resonant beam extraction
Aug 2018	high current tests beam quality measurements
Sep 2018	high current tests beam quality measurements

Main Work Items (year 4)

Oct 2018	Install eRHIC cryogenic adjustments	Apr 2019	high current setup, 1 mA 1 pass and energy recovery
Nov 2018	Install eRHIC amplifyers, RF connectors, power, water, etc.	May 2019	2, 3 and 4 pass setup high current operations
Dec 2018	Install eRHIC cryomodule	Jun 2019	BBU measurements
Jan 2019	Beam commissioning in pulsed mode Beam through first pass, linac phasing path length adjustment dump optics setup	Jul 2019	higher current tests, > 1 mA
Feb 2019	demonstrate energy recovery for 1 pass beam quality measurements	Aug 2019	high current tests beam quality measurements
Mar 2019	beam optics verifications, pulsed beam energy acceptance measurements	Sep 2019	high current tests beam quality measurements

Personnel needs by quarters



Summary

Neither an FFAG loop with a factor of 4 momentum acceptance nor a multi-turn ERL has been built before. **The Cβ FFAG ERL at Cornell will address both of these risk factors for eRHIC** adequately and rather completely.

Cornell and BNL have started to collaborate on the creation of this prototyping facility at Cornell, using ERL components from Cornell

- A DC electron gun
- A low-emittance and high-current injector linac,
- An ERL-merger
- A 10m long CW SRF accelerator module
- A beam stop.

The collaboration has become rather active clearing space, testing components, producing WBS for detailed costing and timeline, and providing an organizing structure.

1st Important eRHIC-ERL prototyping results can be available in 2018 !
Afterwards, the eRHIC cavity can be tested with beam for HOM heating and BBU !

Questions ?